Dark Matter Search at Future Lepton Colliders

Xin Shi

Institute of High Energy Physics
Chinese Academy of Sciences
Future lepton (*electron*) colliders

- **ILC – International Linear Collider**
  - $E_{CM} = 250$ GeV
  - $L = 20$ km
- **CEPC – Circular $e^-e^+$ Collider**
  - $E_{CM} = 240$ GeV
  - 100 km ring
- **CLIC – Compact Linear Collider**
  - $E_{CM} = 380$ GeV (1.5 – 3 TeV)
  - $L = 11$ km (29 - 50 km)
- **FCC-ee – Future Circular Collider**
  - $E_{CM} = 90$-400 GeV
  - 100 km ring
# Time line of future colliders

<table>
<thead>
<tr>
<th></th>
<th>$T_0$</th>
<th>+5</th>
<th>+10</th>
<th>+15</th>
<th>+20</th>
<th>...</th>
<th>+26</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ILC</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.5/ab</td>
<td>1.5/ab</td>
<td>1.0/ab</td>
<td>0.2/ab</td>
<td>3/ab</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>250 GeV</td>
<td>250 GeV</td>
<td>500 GeV</td>
<td>2m$_{top}$</td>
<td>500 GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CEPC</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.6/ab</td>
<td>16/ab</td>
<td>2.6/ab</td>
<td>2.5/ab</td>
<td>5.0/ab =&gt; until +28</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>240 GeV</td>
<td>M$_Z$</td>
<td>/ab 2M$_W$</td>
<td>1.5 TeV</td>
<td>3.0 TeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CLIC</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.0/ab</td>
<td></td>
<td></td>
<td>2.5/ab</td>
<td>5.0/ab =&gt; until +28</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>380 GeV</td>
<td></td>
<td></td>
<td>1.5 TeV</td>
<td>3.0 TeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>FCC</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>150/ab</td>
<td>10/ab</td>
<td>5/ab</td>
<td>1.7/ab</td>
<td>hh,eh =&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ee, M$_Z$</td>
<td>ee, 2M$_W$</td>
<td>ee, 240 GeV</td>
<td>ee, 2m$_{top}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>LHeC</strong></td>
<td></td>
<td>0.2/ab</td>
<td></td>
<td>0.72/ab</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>HE- LHC</strong></td>
<td></td>
<td></td>
<td></td>
<td>10/ab per experiment in 20y</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>FCC eh/hh</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20/ab per experiment in 25y</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Current status of lepton colliders

- **ILC**
  - TDR (500GeV) published on Mar 2013
  - Re-baselined to 250 GeV in 2017: 1711.00568

- **CEPC**
  - CDR released on Nov 2018: [http://cepc.ihep.ac.cn/](http://cepc.ihep.ac.cn/)
  - Input to European Strategy: 1901.02170, 1901.03169

- **CLIC**
  - Published CERN Yellow Reports in 2018: [http://clic.cern](http://clic.cern)

- **FCC-ee**
Dark Matter Searches Classification

To illustrate the basic ideas, I took the sections from CEPC CDR (and selected slides from Matt Reece), which also applies to most of the other lepton collider cases.

1. Electroweak-interacting particles 
   (e.g. but not limited to, SUSY neutralinos)
2. DM interacting with renormalizable gauge-invariant SM portals
3. DM interacting with BSM portals 
   (e.g. leptonic Higgs portal)
4. Model-agnostic 
   (photon + MET, EFT approach)
1. Electroweak DM
Doublet/Triplet DM

Like higgsinos and winos, but bigger Yukawas. Custodial symmetry “blind spot” when $y_1 = y_2$. 

$$y_1 (H \sigma^i D_1) T^i - y_2 (H^\dagger \sigma^i D_2) T^i + h.c.$$ 

Electroweak precision measurements, especially the $S$ parameter, can play a useful role in covering direct detection’s blind spot.
Light singlet DM mixing with heavier EW-charged

- Mostly-bino dark matter in the MSSM, non-thermal relic abundance
- Bino is a pure singlet, couples to the SM only through small mixing parameters, difficult to detect directly
- It can either be detected or constrained through the invisible width of the Higgs boson $\sim 0.24\%$.

$$\text{BR}(H \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0) \gtrsim 0.24\%.$$
2. SM Portals
Dark Photons in Radiative Return

Marek Karliner, Matthew Low, Jonathan L. Rosner, Lian-Tao Wang 1503.07209

Make a dark photon in association with an ordinary photon, and do a resonance search:

\[ e^+e^- \rightarrow \gamma Z_D \rightarrow \gamma \mu^+\mu^- \]
CEPC coverage of Higgs portal matter

- Higgs invisible decay provide the strongest limit in DM mass $\sim 10\text{GeV}$

- The DM is assumed to be either a scalar or a Majorana fermion with a scalar coupling

\[
\Gamma(H \to SS) \propto (1 - 4m_S^2/m_H^2)^{1/2}
\]

\[
\Gamma(H \to \bar{\chi}\chi) \propto (1 - 4m_\chi^2/m_H^2)^{3/2}
\]
3. Beyond-SM Portals
Leptophilic DM

Some portals don’t exist in the SM, at least renormalizably: e.g. a scalar coupling preferentially to leptons but not quarks. Can complete into a 2HDM with a leptonic Higgs. (Brian Batell, Nicholas Lange, David McKeen, Maxim Pospelov, Adam Ritz 1606.04943)

These models can have DM signals but also signals from effects of other particles added, like second leptophilic Higgs.
Muon-philic DM

Qing-Hong Cao, Yang Li, Bin Yan, Ya Zhang, Zhen Zhang
1604.07536

Two new fields with Yukawa coupling to muons:

\[ S\mu_L F \]

Neutral component of S is DM.

Assumes a 0.2% measurement of \( e^+e^- \rightarrow \mu^+\mu^- \) at 240 GeV.
4. Model-Independent
Model-Independent, EFTs

Zhao-Huan Yu, Qi-Shu Yan, Peng-Fei Yin 1307.5740
(Not CEPC-specific)

(Earlier work: Birkedal, Matchev, Perelstein; many others)

“Rayleigh dark matter”

Phrase bound in terms of an operator:

\[ \mathcal{O}_F = \frac{1}{\Lambda^3} \bar{\chi} i \gamma_5 \chi F_{\mu\nu} \tilde{F}^{\mu\nu} \]
Summary

• Future lepton collider programs are very active (circular and linear)

• Good synergies between LHC (and future hadron colliders)

• Dark Matter searches on lepton colliders are complementary to other DM experiments and have unique strength for certain regions

• Welcome for new ideas of DM hunting in lepton environment!
Upcoming Events

CLIC Detector and Physics Collaboration Meeting

27-28 August 2019
CERN

International Workshop on Future Linear Colliders

LCWS2019
Sendai
October 28 – November 1
Acknowledgement

• Xinchou Lou (IHEP)
• Gang Li (IHEP)
• Marcel Stanitzki (DESY)
• Moritz Habermehl (DESY)
• Matt Reece (Harvard)
• Zhen Liu (Maryland)
Backup
$e^+e^- \rightarrow W^+W^-$

Lei Wu 1705.02534: study the pure (pseudo-Dirac) higgsino

WW process also studied from the viewpoint of TGCs as effective operators, e.g.: Ligong Bian, Jing Shu, Yongchao Zhang 1507.02238

Dashed lines: projected LHC search reach (Baer, Mustafayev, Tata 2014)
Dark matter

**Higgsino:**

WIMP dark matter candidate, connected to weak scale naturalness, and gauge coupling unification

When other superpartners decoupled:
- $\chi^+ - \chi^0$ slightly heavier than $\chi^0$
- $\chi^+ \rightarrow \pi^+ \chi^0$ leaving 'disappearing track' in detector

reach Higgsino mass of 1.1TeV, required for DM relic mass density – even with some level of background

**Electroweak precision tests:**

arXiv:1810.10993 - Di Luzio, Gröber, Panicc

Precision measurements of $d\sigma/d(cos\theta)$ in $e^+e^- \rightarrow ff$
sensitive to new states

$\rightarrow$ exclude mass ranges

e.g. for $n=3$ Dirac fermion, $m=2$TeV saturates DM relic mass density: can be excluded by CLIC

**Higgsino 95% Exclusion Reach**

<table>
<thead>
<tr>
<th>$m$ [GeV]</th>
<th>0</th>
<th>200</th>
<th>400</th>
<th>600</th>
<th>800</th>
<th>1000</th>
<th>1200</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 stub</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 stub + $\gamma(50)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 stub + $\gamma(100)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 stub + $\gamma(200)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>380 GeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5 TeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.0 TeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Other states 95% Exclusion Reach**

- $(1.7, e_{DF})$
- $(1.7, e_{CS})$
- $(1.5, 0)_{MF}$
- $(1.5, e_{DF})$
- $(1.5, e_{CS})$
- $(1.3, e_{CS})$
- $(1.5, 0)_{MF}$
- $(1.3, e_{DF})$
- $(1.2, 1/2)_{DF}$

DF=Dirac Fermion, MF=Majorana Fermion, CS=Complex Scalar
SU(3)xSU(2)xU(1) representation; different n-tuplet multiplicities

arXiv:1812.02093 The CLIC Potential for New Physics
FCC-ee discovery potential and Highlights

Today we do not know how nature will surprise us. A few things that FCC-ee could discover:

EXPLORE 10-100 TeV energy scale (and beyond) with Precision Measurements
-- ~20-100 fold improved precision on many EW quantities (equiv. to factor 5-10 in mass)
  \[ m_Z, m_W, m_{\text{top}}, \sin^2\theta_W^{\text{eff}}, R_b, \alpha_{QED}(m_Z), \alpha_s(m_Z, m_W, m_{\tau}), \]
  Higgs and top quark couplings
  model independent «fixed candle» for Higgs measurements

DISCOVER a violation of flavour conservation or universality and unitarity of PMNS @10^{-5}
-- ex FCNC (Z -> \mu\tau, e\tau) in 5 \times 10^{12} Z decays and \tau BR in 2 \times 10^{11} Z \rightarrow \tau \tau
  + flavour physics (10^{12} bb events) (B \rightarrow s \tau \tau etc..)

DISCOVER dark matter as «invisible decay» of H or Z (or in LHC loopholes)

DISCOVER very weakly coupled particle in 5-100 GeV energy scale
  such as: Right-Handed neutrinos, Dark Photons, ALPS, etc...
  + and many opportunities in – e.g. QCD (\alpha_s @ 10^{-4}, fragmentations, H \rightarrow gg) etc....
Path to realizing the CEPC

Chinese Government: “actively initiating major-international science project...”

http://www.gov.cn/zhengce/content/2018-03/28/content_5278056.htm

• focuses on “frontier science, large-fundamental science, global focus, international collaboration, ...”

• by year 2020, 3-5 projects will be chosen to go into “preparatory stage”, among which 1-2 projects will be selected. More projects will be selected in later years.

• The task of selecting the projects, and develop them further falls on the Ministry of Science and Technology (MOST)

• MOST committees formed, are writing the guidelines

• This is a likely path to realize CEPC. We are paying close attention to this opportunity

CEPC team is actively cooperating with the Chinese Ministry of ST to seek to be included in the program
CEPC Project Timeline

- **Pre-Studies (2013-2015)**
  - Government Approval
    - 2019-2021 Big Science cultivation
    - Site selection, geological surveys and civil engineering design
    - Key technology demonstration & system verification
  - 2016.6 R&D funded by MOST
  - 2018.5 1st Workshop outside of China
  - 2018.11 Release of CDR
    - 2013.9 Project kick-off meeting
    - 2015.1 R&D funded by IHEP
    - 2015.3 Release of Pre-CDR

- **Key Tech. R&D Engineering Design (2016-2021)**
  - 2018.2 1st 10 T SC dipole magnet built
  - 15 T SC dipole magnet & HTS cable R&D

- **Construction (2022-2030)**
  - 2022 MoU, international collaborations
  - 2023-2027 Tunnel & infrastructure construction
  - 2022-2027 Acc. components mass production; 2028-2030 installation, alignment & calibration, followed by commissioning
  - 2023 Decision on detectors and release of detector TDRs; 2024-2030 detector construction, installation and commissioning

- **Data Taking (2030-2040)**
  - 20 T dipole magnet R&D with Nb₃Sn+HTS or HTS

- **SPPC Alternatives: ep/eA**

**HTS Magnet R&D Program**

X. Lou
Organize the international working group with close consultation with MEXT.
Report on cost-sharing and governance issues by Sept. 2019

Promote activities to gain a better understanding of the broader academic community in Japan.
- Propose the ILC project to the SCJ Master Plan
- Organize a symposium

Cooperate MEXT to establish the governmental level discussion groups with France and Germany. Also, we need to strengthen the discussion group with the US DOE.

Conducts R&D program at ATF, STF and CFF facilities collaborating with the international teams.
- US-Japan ILC cost-reduction R&D

... and so on.

KEK is making all efforts to realize the ILC as an international project.

- 1st KEK international WG meeting in Granada on May 2019

- Japanese Diet members and MEXT officials visited Germany and France in July 2019

- US DOE official Dr. Paul Dabbar visited Japan and attended the Diet member’s meeting for the ILC in October 2018